Cooperative Detection applied to THz Imaging Cameras

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ABSTRACT

THz technology for developing imaging systems has recently aroused great interest, mainly due to the large number of applications in which these frequencies can be used: security, vision in hard environments, etc.

The technological difficulties involved in producing a large number of detectors at these frequencies, proves to be a serious constrain that limits the possibilities of the whole system. It is frequently necessary for the camera to include some kind of moving mirrors in order to scan the entire vision field.

We propose a method that significantly reduces the number of detectors needed for achieving a certain resolution by means of diffraction that paradoxically is the resolution limiting factor in current imaging devices. The method uses diffraction as a way of achieving spatial diversity and as an anti-aliasing LPF. Decimation is used to reduce the number of detectors.

INTRODUCTION

Charge-Coupled Devices (CCD) are the paradigm of individual non-cooperative detection. Although the elements of a CCD make up an array of sensors, they do not work as one antenna-wise (cooperation among elements), but each one is exclusively responsible for detecting the information that comes to it. This conception, which can be extrapolated to lower frequencies, limits the maximum achievable resolution, the robustness and establishes the complexity of the system. The former is limited by the size of the elements, the spacing among them and the total number of detectors in the array. The robustness is limited to that of a single element since the failure of any of them means the loss of the information the damaged one was supposed to receive. Finally, the complexity increases due to the fact that individual detection itself requires a large number of detectors and therefore a large number of components to control each one of them.

Nowadays it is technologically affordable to take this non-cooperative approach at optical frequencies since components that work in this band are simple and can be produced massively, therefore cheaply, in a highly mastered technology such as silicon or CMOS. On the other hand we have the low THz band which lies between the optical and the microwave domain. Neither optical technology nor the microwave one provide the necessary tools for developing satisfactory solutions at these frequencies. Current devices working in this band rely on complex detectors that need heterodyne receivers to work in an intermediate frequency that present technology can handle. This complexity seriously limits the amount of detectors that can be used in an array. The way that THz camera developers have found to overcome this problem is through progressive scanning techniques.

Since just a few detectors are available, they are arranged in a distribution such that they can capture a portion of the image. This way, the image can be divided into several non-overlapping regions, so that each one is captured at a time. This method allows the composing of a big image out of several smaller ones, but implies problems with alignments and mechanics, usually with mirrors as most designs choose to have the detectors fixed and scan the image through moving reflecting surfaces. Another shortcoming this technique has is the exposure time required (exposure time per region x number of regions) and therefore the difficulty of maintaining the scenario still during that time.

The logical evolution of THz imaging technology is towards achieving a THz CCD. While THz technology is an almost pristine field, GHz technology is not, and combined with several image processing techniques may give us a solution for the low THz band. What makes THz detection so difficult is the need of high quality detectors (i.e. high SNR) for the reasons explained at the very beginning of the introduction. If high GHz band technology is to be used instead of THz one, the image processing techniques have to be directed towards allowing lower quality detectors (i.e. simpler detectors) in the array. Simpler detectors would allow us to put more of them in a single array thus resembling a THz CCD.

We have developed a method that uses spatial diversity and cooperative detection to get round the shortcomings presented above, achieving a more robust and less complex system. In the case of CCDs the way of applying it is forcing each beam of light to scatter (using a pinhole for example) and illuminate not a spot (single detector) but a region, in such a way that the information is now received by several detectors. This represents a step forward in robustness since now the system can tolerate the failure of some of its components because the information is still present in others. Given the fact that spatial scattering using a pinhole is a linear transformation it is possible to reverse it and recover the original spatial distribution of the signal. An important point to highlight is the fact that because the information is received in phase in all detectors, when being reconstructed (spatially), it adds up in amplitude while the noise adds up in power, this allows a smaller SNR in each detector, therefore it can be simpler.

Spatial diversity also offers a second possibility, and that is taking advantage of the fact that the information is received by several detectors to get rid of some of them and calculate their approximate value through interpolation. This technique significantly reduces the number of detectors required for determining the incoming point of the signal and its original value, thus diminishing the complexity of the system. Since decimating implies aliasing, the image has to be band-limited. This does not represent an important constrain as most images have the majority of their components at low (spatial) frequencies.

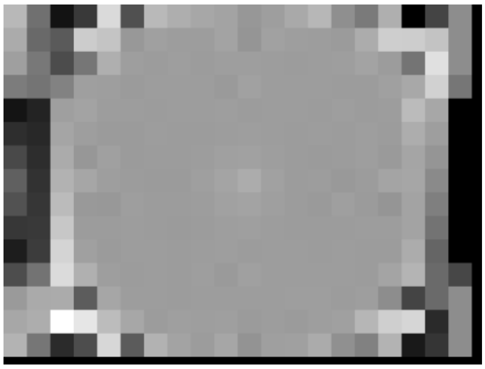
Summarizing, the use of spatial diversity techniques offers the possibility of creating more robust and less complex arrays than those based on single non-cooperative detection allowing the developing of better THz imaging devices.

BACKGROUND INFORMATION

Current imaging technology is mostly based on CCDs. CCDs are set of sensors arranged side by side in a matrix-like layout where each of the elements is the only one responsible for receiving the information that comes to it. The resolution achieved by a particular CCD is determined by the size of its detectors. The smaller they are the better resolution you get (Fig. 1). However resolution cannot be improved endlessly by reducing the size of the detectors. There is a practical limit which is established by the diffraction produced by the system.

Diffraction is a common phenomenon that is present in all optical systems and is studied in depth in literature. In imaging systems, it arises from the fact that any incoming plane wave is spatially windowed by a lens and/or diaphragm. The resulting image is the spatial convolution of the incoming image with the windowing mechanism's Point Spread Function (PSF) [1]. Its main implication is converting point sources into blobs.

The result of capturing an image depends on the relationship between the size of the blobs produced by the windowing mechanism and the size of the detectors at the focal plane. The value obtained at each pixel is the one resulting from integrating all the incoming power into the detector in the exposure time. In current CCD architecture a blob must be small enough to fit most of its energy in a single pixel to obtain a clear image, as is established by the Rayleigh criterion [2]. The maximum resolution achievable is then the one obtained with the smallest detectors that still meet this criterion. Since diffraction establishes the upper achievable resolution limit, the system is said to be diffraction-limited [3].



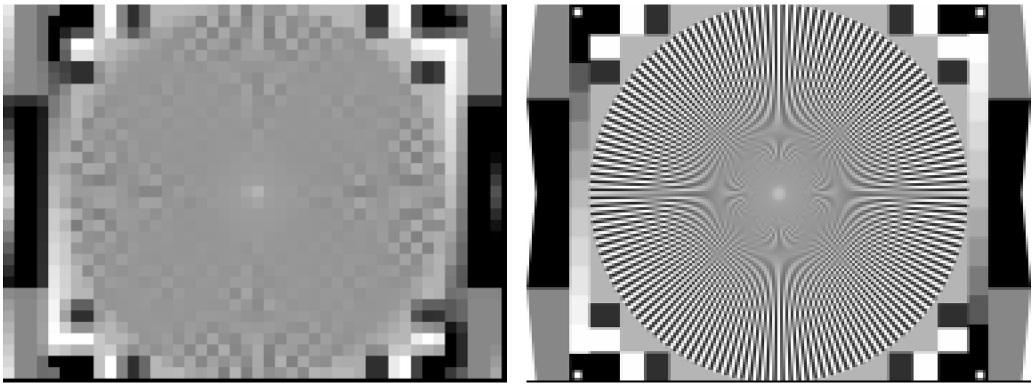


Fig. 1. Simulations results of capturing an image using different sensor sizes.

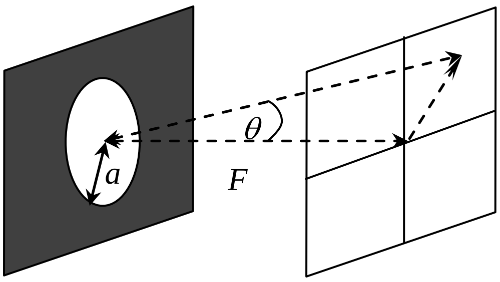
The method we propose uses diffraction in favour of resolution rather than against it (as it naturally does). The key idea is to use diffraction as a way to obtain spatial diversity. We have taken a very well known result, the one regarding the diffraction produced by a circular pinhole. It turns out that a circular pinhole of radius *a* produces a far field [4] intensity pattern, known as Airy Disk, in an observation (focal) plane located at a distance *F* from the pinhole such as [3][5]:

$$I(\theta) = I_0 \left(\frac{2J_1(ka\sin(\theta))}{ka\sin(\theta)} \right)^2 \tag{1}$$

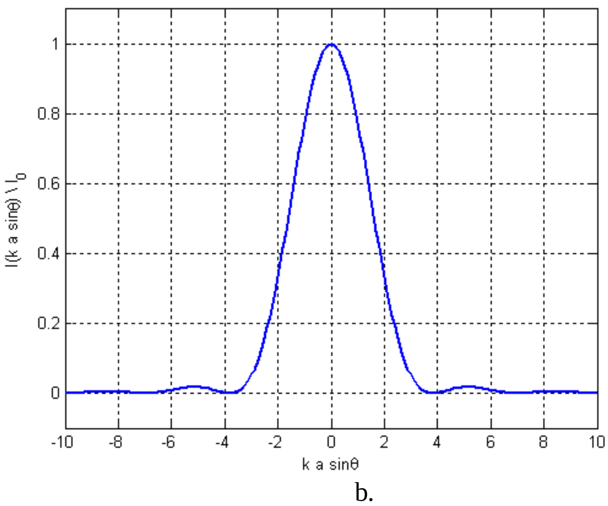
$$I_0 = \frac{P_0 \cdot \pi a^2}{\lambda^2 F^2} \tag{2}$$

Where I_0 is the maximum intensity at the centre of the disk, P_0 is the total incident power on the aperture, J_1 is the Bessel function of the first kind of order one, $k=2\pi/\lambda$ is the wave number and θ is the angle between the axis perpendicular to the aperture and centred on it and the observation point (Fig 2a). The intensity profile is depicted in Fig. 2b.

The Airy Disk is the point spread function (PSF) (i.e. impulse response) of the aperture in the spatial domain, and implies a linear transformation in it. This means that any point source (i.e. any point in the captured scenery) will produce an Airy Disk (when a circular diaphragm is used) in the focal plane. If a normal CCD is used to capture an image in which the Airy Disks are bigger than the sensors, the result is a blurred image as shown in Fig 3b.

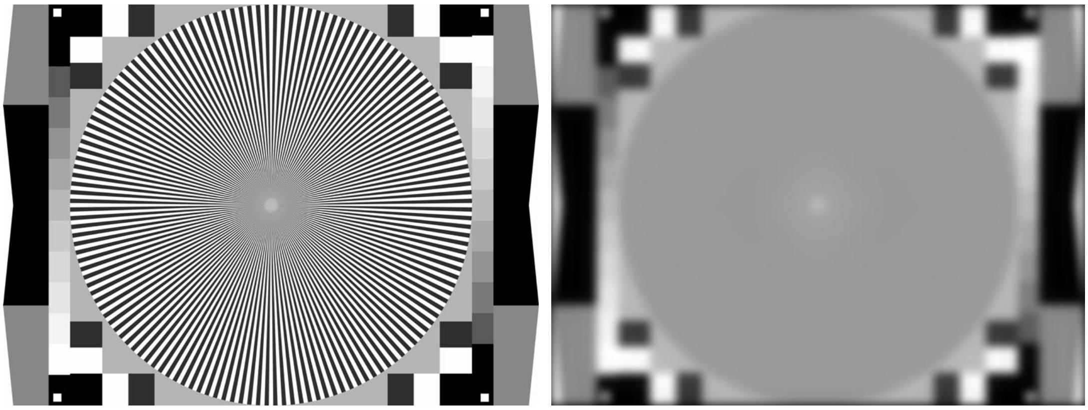


a.



b.

Fig. 2. a. Airy Disk’s scheme of variables. b. Intensity profile.



a. b.

Fig. 3. a. Original image. b. Simulation of a blurred image with a=75μm F=25mm λ=550nm

Even though the images taken under the circumstance stated above (e.g. Fig 3b) are considered to be corrupted, it might be possible to recover them. If we look at an Airy Disk's FFT (Fig. 4) it can be seen that it has no zero values, therefore it is a reversible transformation [4]. The only requirement that has to be met in order to reverse the diffraction effect is that the sampling frequency of the Airy Disk has to be high enough to avoid aliasing. In other words detectors have to be small compared to the size of the disk. Under this premise the result of deblurring Fig 3b is presented in Fig 5.

Now that diffraction is not a limiting factor it would be possible to increment the resolution of the system by means of reducing the size of the detectors below the limit set by the Rayleigh criterion. Another advantage of allowing large Airy Disks to occur is that the information that in classic architectures would be received by a single detector now is present in several ones. This fact increases the system's robustness by making it failure tolerant, which is a characteristic that current CCD technology does not have.

But a further improvement can be made. Given that most of the information contained in an image is located at low spatial frequencies it is possible to allow some degree of decimation by suppressing a number of detectors. Diffraction works as an anti-aliasing LPF in this case. Decimated values can be calculated through interpolation by applying a low pass filter.

It has to be highlighted that this is not a pure signal processing method. Signal processing cannot invent information where there is none, it works only with the information present. If just signal processing is used it would be impossible to detect a source that lies in between the detectors in a decimated array of sensors (Fig 6a). But since diffraction spreads the information across the elements of the array (Fig 6b) it is possible to interpolate the missing values (Fig 6c) and finally reverse the diffraction effect (Fig 6d). In this case the Fig. 6a achieves roughly the same resolution as Fig 6d, but using a quarter of the number of detectors. (Fig 6 is showed for illustration purposes, but does not represent an actual simulation result).

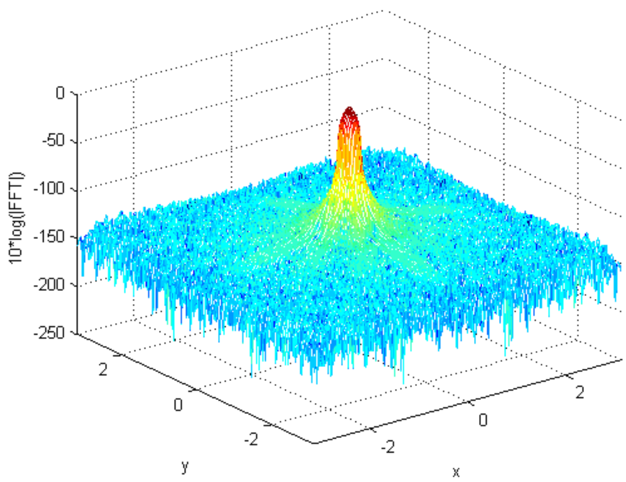


Fig. 4. Airy Disk 2D FFT.

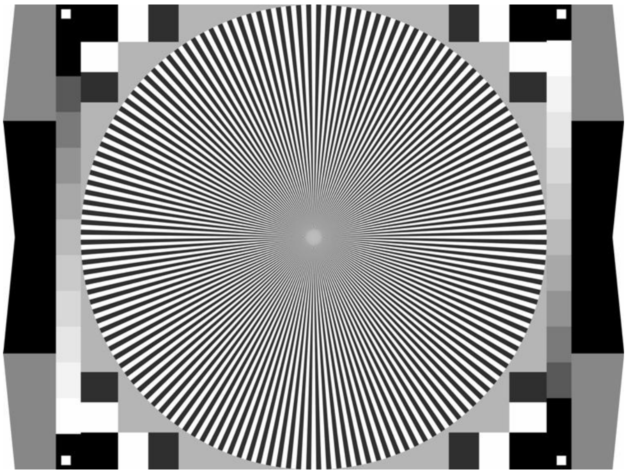
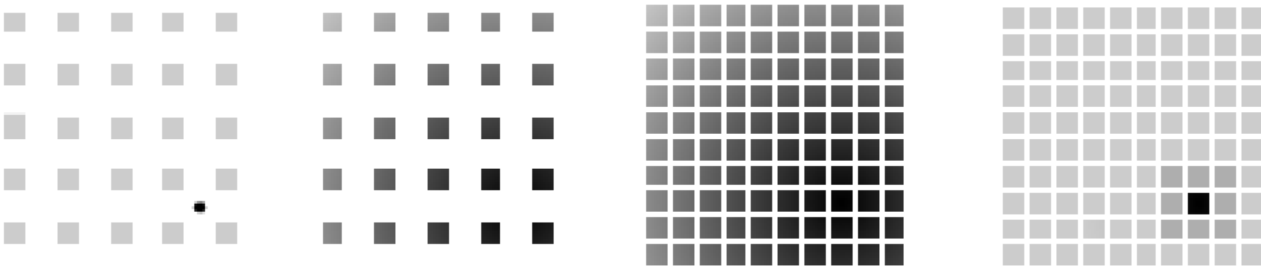


Fig. 5. Image recovered from deblurrng Fig 3 b.



a. b. c. d.

Figure 6. An example of how resolution is improved using the method presented.

THE METHOD

Our method puts together all the techniques stated above, and the images presented in this article are the result of computer simulations. First of all the image (Fig. 3a) is blurred using a pinhole of radius a = 75μm and the detectors are 25 mm away from it. Assuming light at λ=550nm and square detectors of 5.7μm yields that the Airy Disk's radius is approximately 20 pixels wide.

The image is detected by a decimated array of pixels. Several levels of decimation were tested. In Fig. 7 the array has been decimated by a factor of 4.

After the image is captured, the missing values are calculated through interpolation using an LPF (Fig. 8). The interpolation filter has a significant impact on the final result. We have chosen a filter composed of a flat top and Gaussian edges, and its cut-off frequency is adapted to the level of decimation applied.

Fig. 7. Image captured by the CCD.

Fig. 8. Interpolated image.

When the full image is got then it is deblurred using the inverse FFT of the blurring Airy Disk. It has to be noticed that the Airy Disk's FFT has no zero values, therefore it is reversible, but it does greatly amplify high frequencies. If there is noise, the reader might think that this fact would represent a major drawback. This not the case, though, because the LPF used for interpolation eliminates noise at these frequencies.

The resulting image, using 1/16 of the original number of detectors, can be seen in Fig. 9.

RESULTS

The results obtained using decimation factors of 2, 4, 6 and 10 are presented on the right side of Figs. 10, 11, 12 and 13 respectively. The images on the left correspond to the ones that would result from capturing Fig. 3a using a classic CCD with the same amount of the detectors as the array used in our method. Notice that the number of detectors decreases in turn by 4, 16, 36 and 100. Observe that the images on the left are more and more jagged as the decimation factor increases, while the ones with our method do a very good job in maintaining shapes.

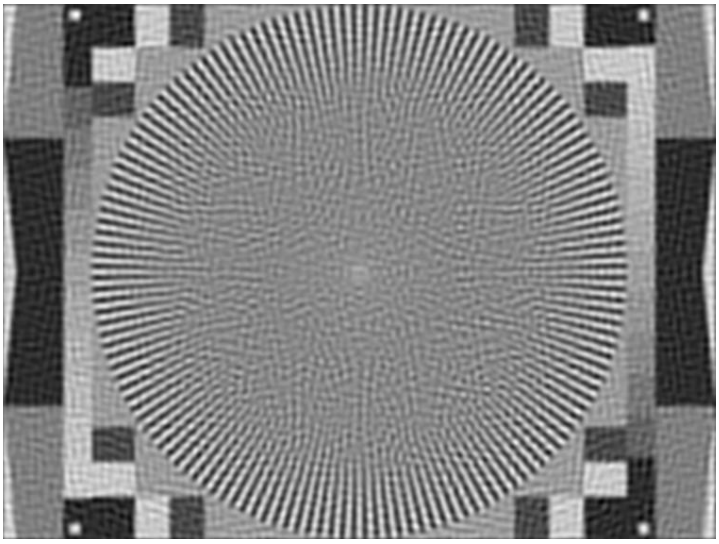


Fig. 9. Resulting image.

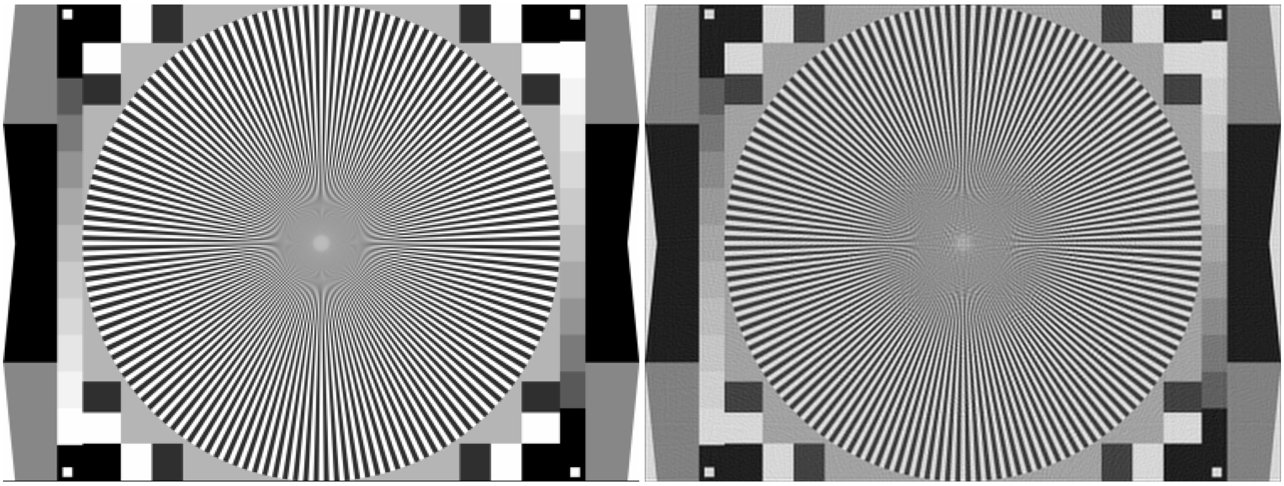


Fig. 10. Decimation factor = 2. Left. Image obtained by a classic CCD. Right. Image obtained with our method.

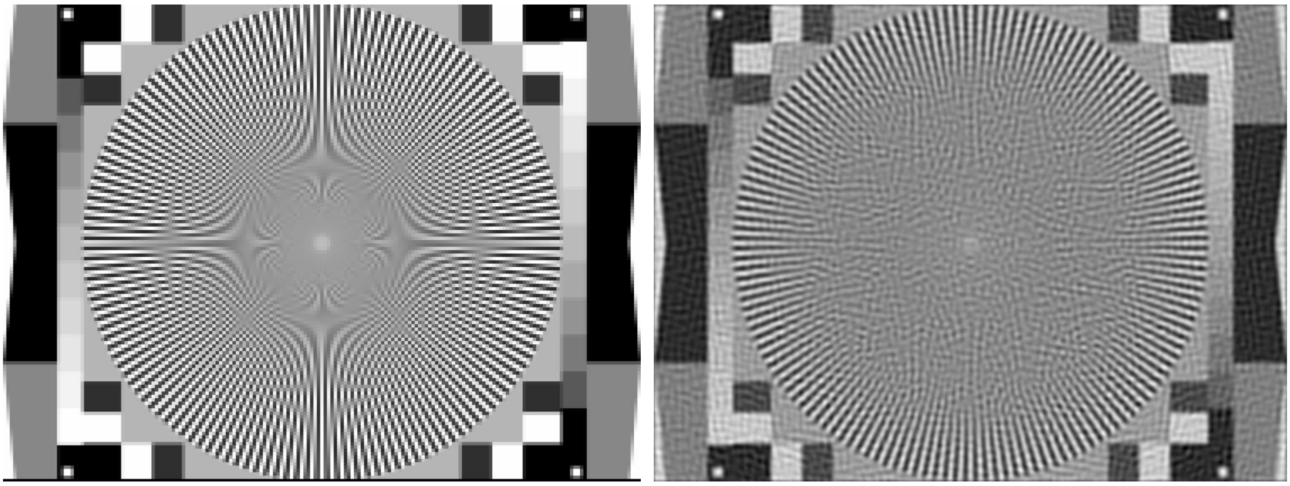


Fig. 11. Decimation factor = 4. Left. Image obtained by a classic CCD. Right. Image obtained with our method.

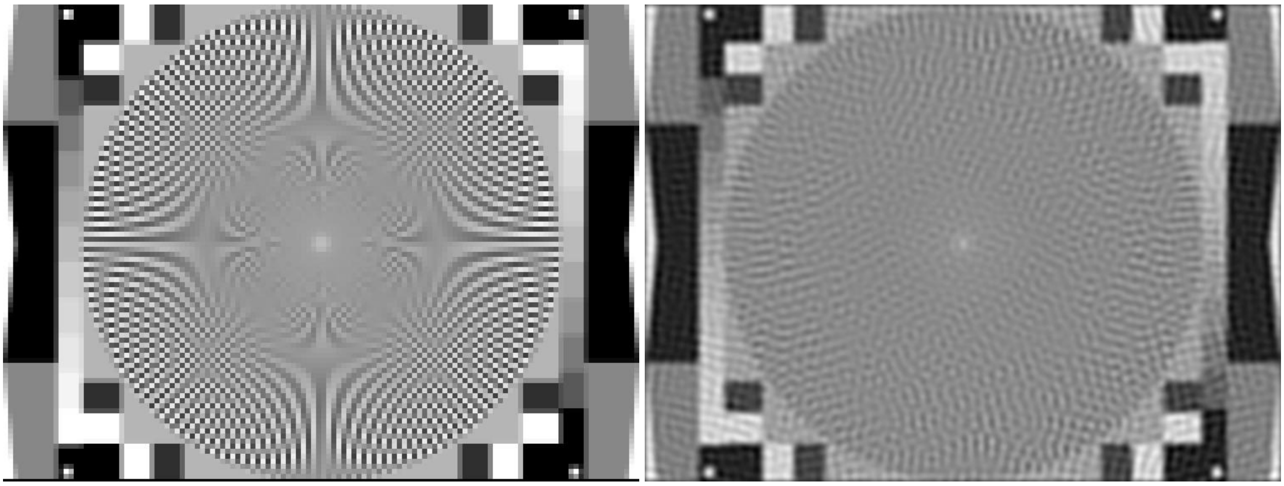


Fig. 12. Decimation factor = 6. Left. Image obtained by a classic CCD. Right. Image obtained with our method.

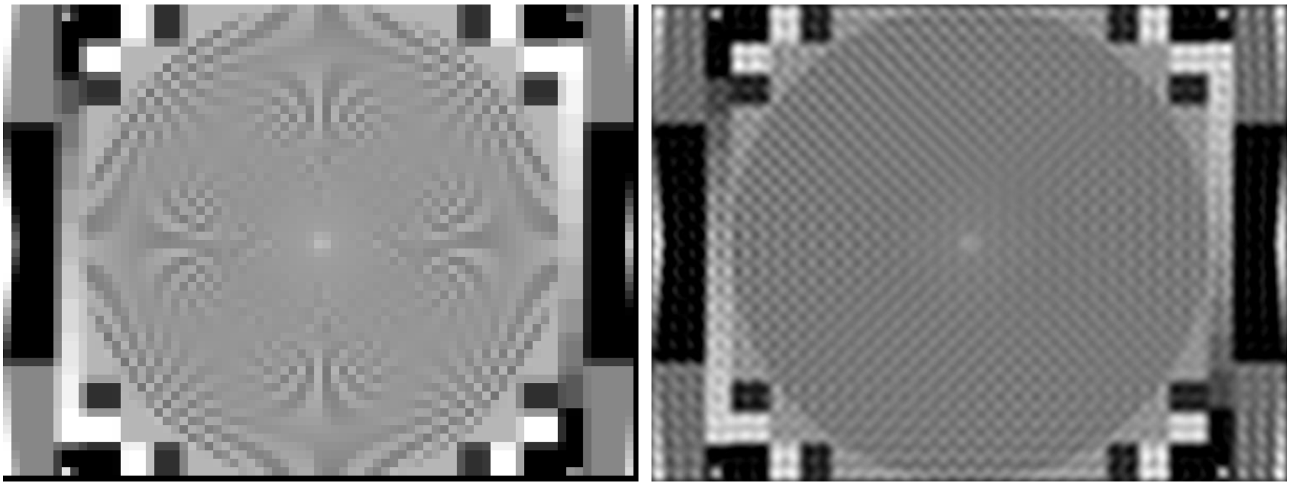


Fig. 13. Decimation factor = 10. Left. Image obtained by a classic CCD. Right. Image obtained with our method.

CONCLUSION

Our method settles the bases for developing a fault tolerant optical system where detector complexity is an issue, as is the case of THz imaging, by allowing fewer sensors. When comparing the result of an image captured with our method to one captured with the same amount of sensors with the classic CCD architecture (sensors side by side), the improvement is noticeable in terms of shapes.

REFERENCES

[1] E. G. Steward, *Fourier Optics: An Introduction*, 2nd ed., Mineola: Dover, pp. 101-106, 2004.
[2] J. W. Goodman, *Introduction to Fourier Optics*, 3rd ed., Englewood: Roberts & Company, pp. 158-160, 2005.
[3] E. G. Steward, *Fourier Optics: An Introduction*, 2nd ed., Mineola: Dover, pp. 38-43, 2004.
[4] O. K. Ersoy, *Diffraction, Fourier Optics and Imaging*, Hoboken: Wiley, pp. 78-110, 2007.
[5] J. W. Goodman, *Introduction to Fourier Optics*, 3rd ed., Englewood: Roberts & Company, pp. 76-79, 2005.